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Research article

Trade-offs between forest carbon stocks and harvests in a steady state – A multi-criteria analysis

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ABSTRACT

This paper provides a perspective for comparing trade-offs between harvested wood flows and forest carbon stocks with different forest management regimes. A constant management regime applied to a forest area with an even age-class distribution leads to a steady state, in which the annual harvest and carbon stocks remain constant over time. As both are desirable – carbon stocks for mitigating climate change and harvests for the economic use of wood and displacing fossil fuels – an ideal strategy should be chosen from a set of management regimes that are Pareto-optimal in the sense of multi-criteria decision-making. When choosing between Pareto-optimal alternatives, the trade-off between carbon stock and harvests is unavoidable. This trade-off can be described e.g. in terms of carbon payback times or carbon returns.

As numerical examples, we present steady-state harvest levels and carbon stocks in a Finnish boreal forest region for different rotation periods, thinning intensities and collection patterns for harvest residues. In the set of simulated management practices, harvest residue collection presents the most favorable trade-off with payback times around 30–40 years; while Pareto-optimal changes in rotation or thinnings exhibited payback times over 100 years, or alternatively carbon returns below 1%. By extending the rotation period and using less-intensive thinnings compared to current practices, the steady-state carbon stocks could be increased by half while maintaining current harvest levels. Additional cases with longer rotation periods should be also considered, but were here excluded due to the lack of reliable data on older forest stands.

1. Introduction

Sustainably managed commercial forests are an important source of renewable biomass while simultaneously sequestering atmospheric carbon (Koponen et al., 2015). Forests can mitigate climate change in two ways:

1) the harvested *flow* of biomass *carbon* displaces a) fossil fuels with wood fuels, and b) materials with high fossil-carbon emissions from manufacturing (e.g. concrete or steel) with wood products;
2) the biomass *carbon stock* of both forests and long-lived wood products sequester carbon from the atmosphere.

There are trade-offs and synergies between the above wood-use and carbon-sequestration options related to managed forests. How should such trade-offs be valued?

In the 'short-term'– up to 2050 or even 2100 – the carbon-stock changes of long-rotation forests seem to be of greater magnitude than the substitution benefits from wood-based bioenergy (Mitchell et al., 2012; Holtsmark, 2013, 2015), with the exception of small-diameter harvest residues (Repo et al., 2011, 2012). Studies related to boreal forests at the country level (Soimakallio et al., 2016; Kallio et al.,2013; Pingoud et al., 2016), regional (Helin et al., 2016) or stand level (Pingoud et al., 2012) also indicate that long-rotation forestry in general – the management and harvest of slowly growing forest biomass stocks for materials and energy – increases atmospheric carbon stocks when compared with almost

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any baseline with less-intensive thinnings or longer rotations. The same conclusion applies even when high fossil-fuel substitution benefits could be achieved with the harvested biomass and, in addition, a substantial share of the biomass could be sequestered into long-lived wood products.[1] Economic analyses using the Faustmann model for finding optimal rotation lengths have come to similar conclusions if changes in the forest carbon stock are priced (van Kooten et al., 1995), particularly if the carbon price increases over time (Ekholm, 2016).

A major reason for the above results is the foregone carbon sequestration. When trees in the growing phase are cut (e.g. in thinnings) their potential carbon sink will be lost, which is compensated only in the long-term by the faster growth of remaining trees and the substitution benefits of the harvested biomass flow, utilized as energy or wood-based materials. It is critical to note that the above results do *not* imply that the forests at regional or country level would be a carbon source,[2] only that their carbon sequestration is weaker *with respect to any no-harvest or less-harvest baselin*e, and this weakening cannot be compensated by the substitution benefits of the higher supply of harvested wood.

A complementary perspective to the transient, i.e. short-term, carbon balance is to consider the carbon balance of steady-state forest management, where the size and age class distribution of the considered forest area remain constant over time. The forest area produces a sustained biomass yield and climate benefit, and different steady-states can be compared against each other in terms of their climate benefits. This perspective, similar to Torssonen et al. (2016) is the subject of the present article. The steady-state condition, termed normal forest in the forestry literature (see e.g. Leslie, 1966), can be pictured in a simplest way as a forest with an even distribution of age classes, where the oldest age class is harvested annually, thus yielding the same harvest each year.

Here, we present steady-state forest management as a problem of maximizing both the biomass carbon stock and harvests, provide two measures for characterizing their trade-offs, and illustrate the concept with simulation results that pertain to forests in mineral soil sites in Southern Finland. The considered management regimes differ in their rotation lengths, thinning intensity and the collection of harvest residues, and result in different steady-state levels of carbon stock and annual biomass yield. While the approach presented cannot answer what is an optimal trade-off between carbon stocks and harvest flows, it renders this trade-off explicit and helps to avoid sub-optimal forest management strategies.

The system boundary of our analysis includes the carbon stocks of wood biomass and the fossil carbon stocks, whose emissions are avoided through use of renewable wood biomass. In a previous study (Pingoud et al., 2010), forest steady-states, together with their wood use chains, were compared applying two indicators: 1) the biomass-carbon stock of forests and wood products in service and 2) the estimated annual fossil-carbon substitution benefits of the wood-use cycles.[3] In this article an indicator integrating these two factors is presented. In the current study the focus is on forest management based on comprehensive data on commercial forestry practices in Southern Finland. The substitution benefits of wood production are considered but the carbon stock of wood products is excluded. An assessment of the potential end use of wood products for each forest management alternative would have required a specific analysis beyond the scope of this article.

2. Methods

We consider here managed forests in a steady state: a forest area is composed of a large number of stands with a uniform age-class distribution for which a constant management regime and clear-cutting cycle is applied repeatedly *ad infinitum*. Such a steady state is often termed *normal forest* (see e.g. Leslie, 1966), and for which the amount of annual harvests and the forest carbon stock remain constant over time. An example of a management cycle of a single stand with a rotation with two thinnings and final fellings is depicted in Fig. 1a. Applying this management strategy for a collection of stands with uniform age-class distribution would lead to the above regional-level steady state.

A management regime such as the one represented in Fig. 1a results in an annual average standing carbon stock and an average annual harvest over the life of a stand for that specific regime. When applied under the steady-state condition, these are equal to a steady-state harvest yield h (tC/ha/year = metric tonnes of carbon per hectare per year) and biomass carbon stock C (tC/ha). This combination generates one point in Fig. 1b. Simulations with multiple management regimes generate a set of such points. The frontier of this set of points separates the set of feasible points (the region under and to the left of the curve) from the infeasible region. Fig. 1b presents the frontier as a smooth concave relationship. Later, in Fig. 2, our numerical simulation results approximate this curve with a piecewise linear surface.

A forest management regime affects both the annually harvested amount of wood and the carbon stock of the forest. Both of these are desirable and should thus be maximized. From the perspective of these two criteria, an ideal forest management regime would maximize both stock and flow; and make voluntary trade-offs between the two criteria when necessary.

In a multi-objective setting, such as the setting described here, an ideal strategy is said to be Pareto optimal when improving one criterion is impossible without worsening the other criterion. The outer boundary of this feasible region is a Pareto curve C_p, and all points inside the feasible region are inferior to those at the Pareto curve: when starting from an interior point, it is always possible to improve either of the criteria without worsening the other, ending up at the Pareto curve.

The steady-states at the Pareto curve C_p involve inherently a trade-off between the carbon stock and harvests. The marginal level of this trade-off at a steady-state (h,C) on C_p equals the slope of the tangent (dC_p/dh) at the point (h,C) (Fig. 1 b)).[4] The choice over the preferred marginal trade-off fixes the slope of the tangent of the Pareto curve, and thus also the corresponding optimal steady-state point on C_p. That is, choosing a desired level of the trade-off determines the optimal forest management regime.

We provide an interpretation with two characterizations for the trade-offs between steady-states. A change in management regimes that shifts the steady-state on the Pareto curve and decreases the steady-state forest carbon stock also enables an increase in the harvests. Such carbon stock loss between Pareto-optimal steady-states can be portrayed as a one-time investment, which provides an additional and perpetual flow of biomass carbon from the forest.

[1] On the substitution benefits of wood construction and carbon sequestration into long-lived wood products, see, e.g., Sathre and O'Connor, 2010; Pingoud et al., 2012; Gustavsson et al., 2006; Forsell et al., 2010, pp. 319–324.

[2] They can still be a carbon sink as a whole. For example, Finland and Sweden are countries with intensive long-rotation forestry and major forest industries, but simultaneously an annually increasing growing stock volume (Koponen et al., 2015).

[3] Pingoud et al. (2010) was a limited case study, where the logs were used as building material of two specific wood-framed multi-store houses, one in Finland and the other in Sweden. The greenhouse gas balance of these two building cases was based on a detailed life-cycle study (Gustavsson et al., 2006).

[4] In economic terms, the Pareto curve can be called a production possibilities frontier while the slope is the marginal rate of transformation.

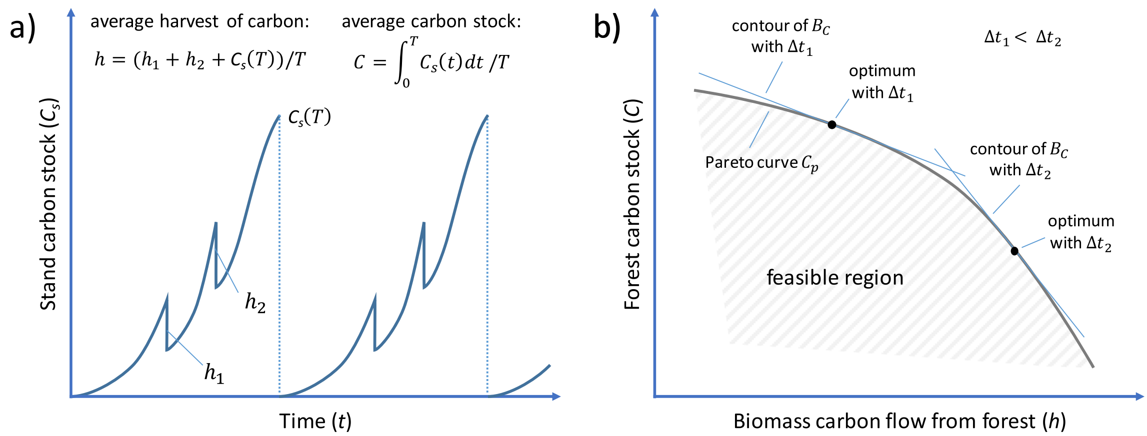

Fig. 1. a) Carbon stock of a single forest stand over time when an illustrative management regime – a rotation with two thinnings (h_1 and h_2) and final fellings at time T – is applied repeatedly. When this management regime is applied to normal forest, the carbon stock and annual harvest flow are proportional to the average carbon stock and harvest flow of a single stand over its rotation period. b) The forest carbon stocks and harvests of a normal forest in all possible management regimes. A single management regime, such as the one illustrated on the left, maps to a single point in the (h,C) plane, and the set of all possible management regimes forms the feasible region. The outer boundary of the feasible region is the Pareto curve C_p. If one characterizes the climate benefit B_c using eq. (1), an optimal steady-state can be found as the tangent of C_p whose slope is determined by the payback time Δt and displacement factor DF.

First, we propose that the total climate benefit of a steady-state forest can be described by the indicator B_c being the sum of the (temporally constant) biomass carbon stock C and the amount of harvested carbon h weighted by its marginal ability to displace fossil carbon elsewhere in the economy within some chosen time frame Δt:

$$B_c = C + DF \cdot \Delta t \cdot h \tag{1}$$

In the above equation it is assumed that the harvested carbon flow h (tC/year) allows for an annual reduction of fossil carbon emissions in the society proportional to the displacement factor DF (Schlamadinger and Marland, 1996). The time frame Δt that characterizes the weighting between carbon stocks and harvests can be interpreted as the carbon payback time for a steady-state (for carbon payback times in a dynamic context, see e.g. Mitchell et al., 2012).

The contour lines of B_c (i.e. when $B_c = C + h \cdot DF \cdot \Delta t = \text{constant}$) are straight lines with a negative slope in Fig. 1b). The longer the payback time Δt, the steeper is the slope, meaning that the substitution benefits from the biomass flow dominate the forest carbon stock. The maximization of the climate benefit B_c leads to a point (or possibly multiple points) at the Pareto curve, where the slope of the Pareto curve corresponds to $DF \cdot \Delta t$:

$$-\frac{dC_p}{dh} = DF \cdot \Delta t \tag{2}$$

Second, following the investment analogy stated above, we propose a new concept of a *carbon return* as an alternative measure, which can allow further interpretation. As the marginal, one-time loss in a forest carbon stock allows a marginal and perpetual increase in harvest, the case is analogous to perpetual annuity, in which a one-time investment yields a constant annual return up to infinity. Following the rate of return formula for the perpetual annuity,[5] the steady-state carbon return r from a marginal change corresponds to the inverse of the slope:

$$r = -\left(\frac{dC_p}{dh}\right)^{-1} \tag{3}$$

3. Materials

We evaluated the steady-state carbon storage and harvest flow of carbon for a forest region under commercial forestry practices representing Southern Finland using growth and yield models of the stand-level decision-support system MOTTI (Salminen et al., 2005; Hynynen et al., 2014, 2015) and the soil carbon model Yasso07 (Tuomi et al., 2009); see Supplementary Material. The MOTTI outputs include tree biomass (foliage, branches, stem, stump, coarse roots and fine roots) and also estimates of litter production including the amount of natural mortality. The litter calculated by MOTTI was used as input to Yasso07. The steady-state (biomass) carbon stock of wood products in service or landfills is omitted in the study. The effect of the constant flow of harvested wood on the fossil carbon balance is described through a single displacement factor DF.

The prevailing management regime of commercial forests in Finland consists of successive thinnings, regeneration felling and the establishment of a new forest. The timing and intensity of management as well as the rotation age are site- and tree species-specific (Rantala, 2011). We assumed that this management cycle goes on to infinity, and the mean values of carbon stock and harvests over the rotation period are therefore the steady-state values for a specific forest stand characterized by tree species and forest type (yield class).

The commercial forests on mineral soils in Southern Finland were reflected by constructing the forest that includes the classes on most common forest sites types and main tree species. The contribution to the region of each forest class was proportional to its share of the total commercial forest area on mineral soils.

Mesic heath (Myrtillus type according to Cajander (1949)) is the most common site type in Southern Finland, populating half of commercial forests in mineral soils. About half of this is spruce dominated (25% share of area) and the other half pine-dominated (25%). Spruce-dominated herb-rich heath (Oxalis-Myrtillus type) covered 27% of commercial forests in mineral soils. Dryish heath

[5] The return to a perpetual annuity is the annuity divided by the investment.

(Vaccinium-Myrtillus type) covered 20% and dry heath (Calluna type) 3%, both typically dominated by pine. These five forest classes represent about 74% of the total area of commercial forests in Southern Finland (10.8 million hectares) (Finnish Forest Research Institute, 2013).

For each forest class, we applied a number of alternative management schedules from no management (only regeneration and final felling) to very intensive commercial thinnings (very low stocking level). All schedules ended with a clear cut. In addition, we varied the length of the site-specific rotation cycles: normal (according to silvicultural guidelines), 20 and 40 years longer, and 20 and 40 years shorter. In the MOTTI simulations the timing of the thinnings and the clear cut varied according to forest site type and tree species. Altogether there were 30 combinations of management schedules and lengths of rotation period that cover well all options of commercial forest management in the Southern Finland. In addition to the 30 forest management alternatives, four options for collecting harvest residues were considered; nothing, only crowns, only stumps, or all residues were removed. This makes a total of 120 combinations of forest management schedules and residue harvesting. They are summarized in Table 1 and described more closely in the Supplementary Material.

We fed the average steady-state litter production over rotation period predicted by MOTTI to Yasso07 and calculated steady-state soil carbon stocks for each forest type – tree species combination for all the 120 forest management and residue harvesting combinations. The litter from MOTTI to Yasso07 was adjusted according to the residue harvesting alternative. We calculated the steady-state of soil carbon by running the Yasso07 from an arbitrary initial value until carbon stocks did not change any more.

The steady-state values of carbon stock for management schedules and rotation periods, u_i, $i = 1, \ldots 30$, and four options of harvest residue recovery, o_j, $j = 1 \ldots 4$, $\in${*no recovery of harvest residues, only crowns, only stumps, all residues*} were calculated as

$$CSS(u_i, o_j) = \sum_{k=1}^{5} a_k \times (C_{bk}(u_i, o_j) + C_{sk}(u_i, o_j)) \quad (4)$$

where C_{bk} and C_{sk} are steady-state values of biomass and soil carbon stocks for tree species and forest type combination k, a_k is proportion of forest area combination k occupies currently in the Southern Finland (see Supplementary Material and Table 1). There were 5 tree species and forest type combinations. The harvested carbon for each management schedule u_i and option of harvest residue recovery, $o_j \in$ {*no recovery of harvest residues, only crowns, only stumps, all residues*}, was calculated analogously to Eq. (4) as

$$HSS(u_i, o_j) = \sum_{k=1}^{5} a_k \times h_k(u_i, o_j) \quad (5)$$

where $h_k(u_i, o_j)$ denotes the mean value of harvested biomass over the rotation (steady-state value) for management u_i and harvest residue recovery option o_j. The values of $h_k(u_i,o_j)$ were predicted by compartment-specific tree biomass equations of MOTTI. The points $(HSS(u_i, o_j), CSS(u_i, o_j))$ are points in the (h, C) plane (see Fig. 1b). The merchantable stem was harvested in all cases, branches and non-merchantable top were taken in the case of *only crowns*, stumps and half of coarse roots were taken in the case of *only stumps*, and *all residues* included all of them.

Table 1
A summary of applied management strategies in the calculations.

Management method	Applied strategies
Rotation length	48/68/88/108/128 years
Thinnings	no management/no commercial thinnings/mild/normal/intensive/very intensive
Residue harvesting	no/crowns/stumps/both

4. Results

Following the presentation used in Fig. 1b, Fig. 2 presents the steady-state harvested carbon and carbon stocks of the simulated management strategies,[6] and an approximate Pareto curve as linear segments between the peripheral points. The Pareto curve can be interpreted as a result of data envelopment analysis over the set of discrete management regimes. The figure also presents carbon payback times and carbon returns along the Pareto curve. The amount of harvested carbon ranges from 1 to 2 tC/ha/yr, and the carbon stock from 100 to 300 tC/ha. A large number of the steady states are deep inside to the feasible region – i.e. relatively far away from the Pareto curve – indicating that those steady states allow considerable improvements in both carbon stock and harvested carbon. In case carbon stocks of wood products would have been included in the study all these points would have been shifted slightly[7] upwards.

On the Pareto curve, the marginal trade-offs between harvested carbon and forest carbon stocks vary considerably along the curve. The trade-off between the leftmost points of the Pareto curve imply a payback time of 29 years (assuming[8] $DF = 1$) or a carbon return – as expressed in equation (3) – of 3.4%. When moving towards right on the curve, however, the payback times increase and carbon returns decrease rapidly. For the rightmost pair of points, the payback time is almost 2000 years and the carbon return around 0.05%.

Fig. 2 can be also used to consider the climate benefit B_c (eq. (1)) by fixing the payback time Δt and displacement factor DF. With $\Delta t = 0$ or $DF = 0$, the contour lines of B_c are horizontal as no substitution benefits are accounted from harvests. In such a case the maximal value of B_c is nearly 300 tC/ha in Fig. 2, corresponding to the highest carbon stock value. With high substitution values, the contour lines of B_c are nearly vertical and the best scenario is the one with highest wood production (nearly 2 tC/ha/yr). In such case the relative importance of forest-carbon stocks is negligible.

As a purely illustrative example for B_c, one can observe that by choosing $\Delta t = 100$ years and $DF = 1$ the maximal value of B_c is equal to 422 tC/ha. Fig. 2 provides also contours B_c drawn at a sub-optimal points for comparison, using the same Δt and DF choices as above. These sub-optimal management regimes would have B_c of 365 and 288 tC/ha, i.e., reductions of 14% and 32%, respectively, in the

[6] However, the management schedules "no commercial thinnings" and "very intensive thinnings" are excluded from the results due to their high proximity with "no thinnings" and "intensive thinnings". This omission does not affect the Pareto curve or other relevant results.

[7] A rough estimate based on a direct inventory of carbon stock of sawn wood and wood-based panels in Finland (Forsell et al., 2010, pp. 319–324) and their historical export rates (Finnish Forest Research Institute, 2014) suggests that the existing carbon stock of wood products would be of the order of 7% of the carbon stock of trees in Finnish forests (of the order of 800 Tg C according to Liski et al. (2006)). However, the percentage could be much higher in case demand for wood would be directed towards long-lived wood products.

[8] For simplicity, $DF = 1$ is used in the numerical examples, although we are well aware of the difficulties in estimating the factor. As the emission factors of wood-based fuels are in general higher than of fossil fuels (see, e.g., IPCC, 2006; Vol.2, Tables 2.2 and 2.3), DF in energy substitution is usually <1. Taking into account all the fuel cycle emissions (mining, drilling, transport, refining etc.) and the efficiency of energy conversion might change the picture. In addition, market effects have also an influence on DF.

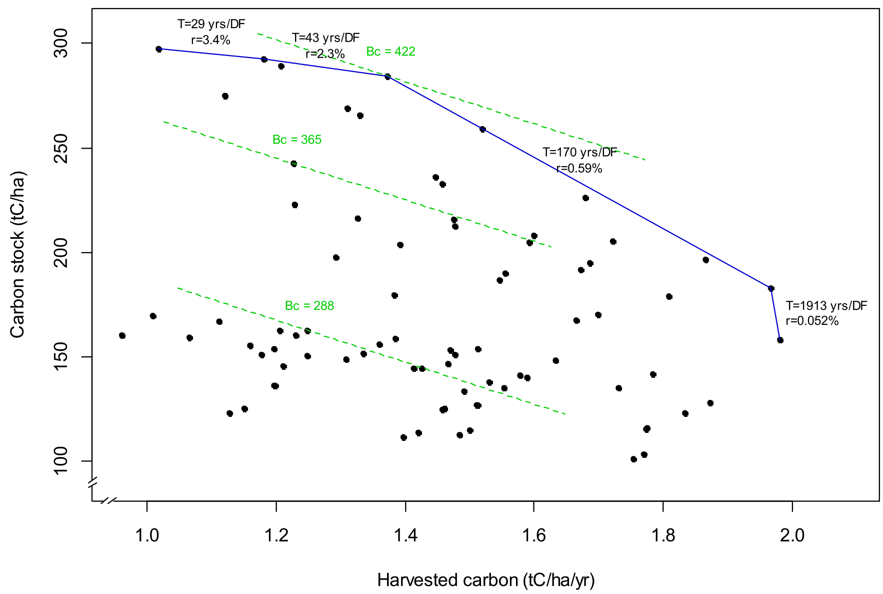

Fig. 2. The stock and harvested carbon of the considered management regimes in a steady-state. The Pareto curve is drawn as linear segments between the boundary management regimes. The carbon payback times and carbon returns are presented for transitions between these points. Three illustrative contours of B_c with $\Delta t = 100$ *yrs* and $DF = 1$ are shown as green dashed lines; the uppermost being the optimal one with these illustrative parameters and the others showing the value of B_c at two suboptimal points in the feasible region. (Units: tC = carbon stock in metric tonnes, ha = hectare, yr = year).

climate benefit B_c with the illustrative Δt and DF parameters.

To portray how the applied management strategies affect the steady-state carbon stocks and harvests, Fig. 3 presents the same steady-states in (h, C) plane as in Fig. 2, but now differentiated over average rotation length, thinnings and removal of harvest residues. The Pareto curve is composed of points that have long rotation lengths and no or mild thinnings.

The figure reveals very distinct patterns between the applied strategies. Both the rotation length and thinning intensity have a considerable impact on the steady-state carbon stock. With normal or intensive thinnings, the carbon stock remains below 170 tC/ha even with the longest rotation lengths, and lengthening of rotation has mainly an impact on the harvested amount. For mild or no thinnings, however, lengthening the rotation increases carbon stocks considerably, while the impact on harvested amount is comparable to cases with normal or intensive thinnings. Short rotation length (48 years) produces low carbon stock and harvests, and lengthening rotations from this improves both carbon stocks and harvest levels in all cases. The largest flow of harvested carbon is achieved with an average rotation length about equal to 64 years

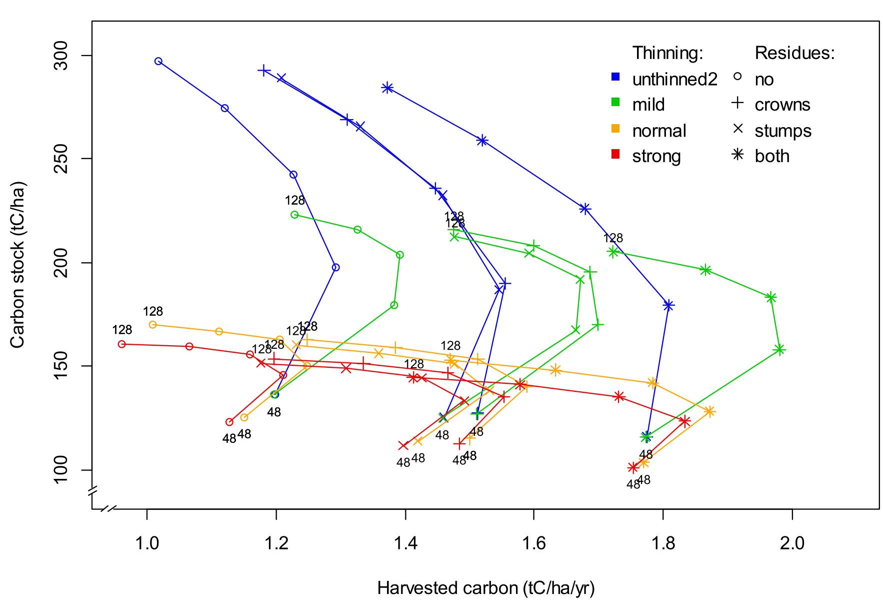

Fig. 3. Comparison of harvest rates and carbon stocks with different forest management strategies. Thinning intensity is indicated with color and residue harvesting with marker type. Points with different forest rotation ages are connected with lines for each combination of thinning and residue harvest strategies. The extreme values of considered rotation ages, ranging from 48 to 128 years, are indicated with a number by the data point.

in all thinning regimes. This suggests that this rotation length covers suitably the period of most vigorous growth when consequently the average yield is highest. With longer rotations the growth rate is lower, reducing the average yield.

Harvesting of residues has a similar impact in all permutations of rotation length and thinnings. The collection of crowns and stumps after harvest increases the harvested amount of carbon considerably, but has only a minor impact on the forest carbon stock. The main reason behind is that residues gradually decay if left on site at harvest, and therefore residues contribute to the carbon stock only in limited amounts. The decay rate is higher for crowns and branches than for stumps, and therefore the impact on stock is smaller for crowns.

In the set of management strategies considered here, maximum carbon stock is achieved with the longest rotation length and no management, and the maximum harvests are attained with an average rotation length of 68 years and mild thinnings. To compare the trade-offs between carbon stock and harvested carbon, the shortest payback times and the highest returns at the Pareto curve – as presented in Fig. 2 – are associated with the collection of harvest residues; the payback times being around 30–40 years and the carbon returns between 2.3% and 3.4%. Shortening the average rotation from 128 to 108 years in the no-management case, and a shift from no management to mild thinnings both corresponded to a payback time around 170 years or a return around 0.6%.

The comparison of steady states under different forest management strategies suggests that significant improvements could be made in the perspective of steady-state stocks and harvest flows of carbon. Current management practices in Southern Finland, to which our numerical examples pertain, comprise average rotation ages around 60–80 years, normal thinnings and a varying level of harvest residue collection. Such points are well inside the feasible region and far from the Pareto front. By switching from such management strategy to no or mild thinnings and extending the rotation age, the carbon stocks could be increased by a factor of 1.5 if residues are initially collected, or even by a factor of two if no residues are initially collected, at a given level of harvested volume in terms of carbon content. This change, however, would also affect the quality of harvested wood, resulting potentially in less-favorable displacement factors. Due to milder thinnings, the share of heavier logs will be lower in final felling, reducing the potentially the displacement factor and revenues from timber sale.

Moving away from the Pareto-efficiency concept, the carbon payback times and carbon returns can also be defined for individual changes in the management regime. As is evident from Fig. 3, the steady-state carbon stocks and harvests depend on the combination of individual management options. Consequently, no single value of carbon payback time and carbon return exists for each management option, and therefore these values are presented as ranges in Table 2 dependent on other management options implemented in each steady-state regime. Despite this, clear patterns emerge. Regarding rotation length, extending average rotations from 48 to 68 years provides an improvement in both criteria, whereas further extensions creates a trade-off between the stock and harvest levels, although with an increasing carbon return and shorter payback times towards 128 years. Changing thinnings from intensive to normal or from normal to mild also yields improvements in both criteria, but from mild to no management can also result in a trade-off. Based on the results it is evident that denser stands with more trees per hectare would result both in higher biomass carbon stocks and higher wood production. The collection of forest residues, however, produces consistently a trade-off between stock and harvest with payback times around 30 and 40 years, or alternatively carbon returns between 2.3% and 3.4%.

5. Discussion and conclusions

We have presented a method that allows analyzing long-term steady-state impacts of forest management regimes in terms of carbon stock and harvest flow. Under Pareto-optimal steady-state management regimes, an inherent trade-off exists between the stock and flow. The rate of this trade-off can be described with the carbon payback time or carbon return, accounting also for the displacement effect of the renewable wood biomass with respect to scenarios with less wood production. With this approach, it is possible to deduce Pareto-optimal forest management regimes under a desired carbon payback time or carbon return. Our procedure suits best for analysis of managed and even-aged forests, in which the cycles of growth and clear cutting are employed in a long-term manner. Calculations similar to carbon balances of this study could be carried out with cumulative radiative forcing as the climate indicator (see e.g. Pingoud et al., 2012).

We used the method to evaluate multiple forest management regimes with differing rotation lengths, thinning intensities and harvest residue collection in commercial forests of Southern Finland. The method could in principle be applied to continuous-cover silviculture as well. We found the well-documented result (see e.g. Helin et al., 2016; Mitchell et al., 2012) that decadal payback times favor larger carbon stocks over harvests in boreal forests, i.e., no management or mild thinnings and very long rotations. The trade-off would turn to the favor of more extensive harvests only with payback times over hundred years, or

Table 2
Carbon payback times and carbon returns for changes in individual options of the forest management regime: rotation length, thinnings and the collection of residues. For each management option, the table presents the range of paybacks time and carbon returns due to a change in the management option in question, where the range arises from the combinations of all other management options. A negative carbon return or “impr.” in the place of payback time indicates an improvement in both carbon stock and harvest levels; positive values indicate a trade-off.

Rotation length:				
	48 → 68	68 → 88	88 → 108	108 → 128
T·DF	impr … impr.	impr … 117	37 … 309	11 … 224
r	−0.5% … −0.1%	0.0% … 0.9%	0.3% … 2.7%	0.4% … 8.7%

Thinnings:			
	intensive → normal	normal → mild	mild → no
T·DF	impr … impr.	impr … impr.	impr … 93
r	−1.0% … −0.5%	−0.5% … 0.0%	−0.5% … 1.1%

Residues:			
	no → crowns	no → stumps	no → both
T·DF	29 … 30	43 … 43	35 … 37
r	3.4% … 3.4%	2.3% … 2.3%	2.7% … 2.8%

conversely carbon returns below 1%. The numerical results indicated that it would be possible to increase forest carbon stocks by a factor of 1.5–2 without diminishing the harvests – in carbon terms – when compared to current practices. This could be achieved by increasing rotation length and decreasing thinning intensity, resulting in denser stands but at the expense of production of large-diameter logs.

Some caveats should be noted on the approach and the numerical results. The trade-off was measured between the stock and flow of carbon. This disregards the quality of harvested wood, which affects the profitability of wood production and potential climate benefits from displacement effects and carbon sequestered in wood products. Low-quality wood material might be suitable mainly for energy, implying a lower displacement factor (and in addition, potentially lower wood-product stocks, which were excluded from the current study). Regarding our numerical examples, it should be noted that the feasible region was limited to average rotation ages up to 128 years due to the limited empirical data available for older stands in Finland. Expanding the feasible region through additional data on older stands would give a more comprehensive view on the feasible and Pareto-optimal steady-states. With longer rotations, however, natural disturbances (e.g. storm damages and insect outbreaks) resulting in increased mortality become more important, and need to be included in the steady-state calculations.

The method does not provide straight answers how the transition to a new forest management regime should be carried out in practice and what incentives would encourage forest-owners to shift management practices accordingly. Demand for wood material exists, and it might increase in the future, should the economy shift from non-renewable raw materials towards renewable ones. Sudden shift to e.g. a longer rotation period or lower milder thinning would cause disruptions on wood supply. Moreover, the steady-state perspective does not represent accurately an individual forest-owners' problem setting, e.g. regarding optimal rotations under time-preference and carbon pricing (see e.g. Ekholm, 2016).

The basic dilemma of long-rotation forestry from the climate and carbon balance point of view is the cyclic nature of the carbon sink of tree biomass: in order to maximize the carbon uptake from the atmosphere the stands must be cut regularly, implying a continuous rotation of stands. However, if the harvested carbon is released to the atmosphere, there will be no net carbon sink to compensate the fossil carbon emissions, only the potential fossil-carbon substitution benefits due to wood-based energy or materials. In addition, a substantial fraction of harvested wood could be sequestered into long-lived wood products.

Currently, both the total increment and growing stock volume of forests in Finland are in a growing phase, despite the increasing trend in annual drain (E-yearbook of food and natural resources statistics for 2015). This is explained by the age-class structure, an increase in average density of stands and diameter of trees, which are results of intensive management of commercial forests in Finland, and also the warming climate (Henttonen et al., 2017). The forests seem to be transitioning into a state in the upper right corner in Fig. 1, i.e., an improvement both in terms of carbon stocks and harvest. However, in the longer run, maybe within some decades, the total increment will eventually start decreasing. How long and according to which management practices should the (net) carbon sequestration into tree biomass be continued – possibly at the expense of future wood production? After the transient phase, the trade-off between stocks and harvest becomes again topical. The issue of sustainable long-rotation forestry is essentially a question of an optimal steady state.

While the Pareto-optimality perspective presented here can support the decision-making between climate change mitigation and wood production, the optimal trade-off between carbon stocks and harvests is left open for the society to decide. The Pareto-optimality principle cannot answer how short the payback times – or conversely, how high the carbon returns – should be. The trade-off is an intertemporal problem over a one-shot change in carbon stocks to a recurrent flow of wood material up to infinity. Choosing an ideal balance between the two is inherently hard, as the benefits from both of the carbon stock and material flow accrue over a very long timeframe. One possible option could be application of a mixed-strategy, where a sufficient forest area is dedicated to carbon sequestration and the commercial forests are managed as efficiently as to possible in order to guarantee wood production.

Valuing changes in carbon stocks might be relatively easy, but what value should be given for the chain of harvests reaching to infinity? Without discounting, the value of this perpetual material flow would be infinitely large, suggesting a steady state that maximizes the material flow. If the values of future material flows are discounted, the chosen discount rate has a momentous impact on the valuation. It has been suggested (Weitzman, 1998) that the distant future should be discounted with the “lowest possible” rate. But even this perspective is not comprehensively accepted, and a controversial debate on the appropriate rate has taken place in the climate change setting (see e.g. Nordhaus, 2007; Weitzman, 2007). Although we are not able to answer this long-standing issue here, our approach of finding Pareto-optimal steady states makes this trade-off explicit.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2017.12.076.

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